Detailed simulation of electrical demands due to nationwide adoption of heat pumps, taking account of renewable generation and mitigation.

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Abstract

This study quantifies the increase in the peak power demand, net of non-dispatchable generation, that may be required by widespread adoption of heat pumps. Electrification of heating could reduce emissions but also cause a challenging increase in peak power demand. This paper expands on previous studies by quantifying the increase in greater detail; considering a wider range of scenarios, the characteristics of heat pumps and the interaction between wind generation and demand side management. A model was developed with dynamic simulations of individual heat pumps and dwellings.

The increase in peak net-demand is highly sensitive to assumptions regarding the heat pumps, their installation, building fabric and the characteristics of the grid. If 80% of dwellings in the UK use heat pumps, peak net-demand could increase by around 100% (54GW) but this increase could be mitigated to 30% (16GW) by favourable conditions. Demand side management could reduce this increase to 20%, or 15% if used with extensive thermal storage. If 60% of dwellings use heat pumps, the increase in peak net-demand could be as low as 5.5GW.

High-performance heat pumps, appropriate installation and better insulated dwellings could make the increase in peak net-demand due to the electrification of heating more manageable.

Highlights

- Widespread (80% of dwellings) use of heat pumps could increase UK peak net electrical demand by 100%.
- A combination of measures could reduce this peak increase to approximately 30%.
- Demand side management has potential to further reduce the peak increase to 20%.
- Extensive thermal storage could further reduce the peak increase to 15%.
- The increase in peak net-demand due to 60% of dwellings using ASHPs could be as low as 5.5GW.

Abbreviations

ASHP	Air Source Heat Pump
DSM	Demand Side Management
MR	Market Rules (a pathway description developed by the ‘Transition Pathways’ project)

1. Introduction

1.1 Significance of the peak power demand associated with heat pumps

Domestic heating must be substantially decarbonised if goals for the reduction of carbon dioxide emissions are to be achieved. Many transition pathways for the UK envisage that a significant share of emissions reductions will be achieved through the electrification of heating in conjunction with the decarbonisation of electricity [1], [2]. However, the widespread use of heat pumps would pose significant challenges. This paper quantifies the increase in the peak demand which might occur under a range of scenarios; indicating the extent to which favourable conditions may mitigate it.

Quantification of the challenges relating to peak power demands is of value in assessing the overall merits and impacts of a strategy that involves electrification of heating [3], [4]. This was recognised in the UK Energy Research Centre's recent reports in which the potential role of thermal storage was explored [5] and the cost of an estimated 40GW increase in peak demand was presented as a barrier to the widespread adoption of heat pumps [6].

1.2 Existing studies

Pudjianto et al. and Gan et al. have investigated the cost implications of heat pumps on the UK grid (at grid and distribution levels) and the potential for Demand Side Management (DSM) to reduce them [7], [8]. These studies extrapolated from the heat demands of 21 properties to estimate that a 56% (45GW) increase in peak electrical demand due to heat pumps could be reduced to 18% by the use of DSM. Sansom and Strbac [9] synthesised heat demand from empirical data on daily national (UK) gas consumption and heat demand at 81 domestic sites. A similar approach was taken by Munuera and Hawkes [10], who estimated that a 33GW increase in peak demand could occur if half of UK dwellings use heat pumps. More recently, Boßmann and Staffell [11] analysed the contribution of different demands to future peak load, concluding that a million extra heat pumps could add 1.5GW to peak demand. These top-down approaches offer a good level of confidence for results relating to similar conditions but are unable to capture the full effect of more fundamental changes in the way that the heat pumps operate.

Other studies have used more detailed models to investigate the implications on the electricity supply system but have focussed on different issues. Several studies ([12]–[17]) use bottom-up, detailed models to analyse impacts relating to a wide range of microgenerators but focus on power flows occurring within the distribution infrastructure rather than across the whole grid. Papadaksapopoulos et al. [18] demonstrated the potential for a pool market mechanism to deliver flexibility in heat pump operation. Their analysis captured the dynamic effect of altering the heating pattern, but focussed on a typical day with current grid conditions. Hedegaard and Balyk [19] found an optimised mix of heat pumps and thermal storage but did not model the variation in the performance of the heat pumps. Barton et al. [20] analysed the effect of a range of possible future demands and the potential of DSM by considering "equivalent electrical storage". Similarly, Boait et al. [21] modelled the effectiveness of DSM but, in order to consider a wide variety of loads, these studies did not model the performance of the heat pumps in detail.

However, the performance of heat pumps is highly dependent upon the conditions in which they operate [22], [23]. Detailed studies have highlighted challenges with the use of thermal storage that may limit the benefits of load shifting [24], [25]. Although fixed time-of-use strategies have the potential to reduce peak demands [26], there are advantages to more dynamic systems [27]. There are significant feedback loops between the operation of heat pumps and the management of the grid that should be modelled when analysing this challenge.

1.3 Novel contribution of this study

This paper quantifies what the increase in peak electrical demand might be in the UK. It is the increase in the peak demand, net of non-dispatchable generation (i.e. that which must be satisfied by dispatchable generating plant) that is of principal interest here. The analysis covers a wider set of conditions than previous studies in order to provide insights into the factors that affect the peak. These include:

- Nominal performance and installation practises used with the ASHPs
- Building insulation standards

- Changes in climate
- Interaction with wind generation variability
- The potential for DSM to reduce the peak net-demand
- The effect of introducing thermal storage

The results of this study are specific to the context of hypothetical UK grid systems but the insights are relevant to many similar national grids that may face comparable challenges. The paper expands upon previous research by combining the insights from detailed dynamic thermal models of Air Source Heat Pumps (ASHPs) and buildings with assessment of their combined effect at the grid level. This approach enables the study to take account of the:

- Extent to which heat pump operation is flexible; the potential for flexibility is an important feature of their operation but has limits and performance implications that are overlooked in simplified models.
- Interaction of this flexibility with the net-demand for generation after wind generation. The results for 0.1% of the duration of the simulations are far more extreme than those which would be reported if the simulations only covered typical days.
- The effect of the flow temperature from the ASHPs on their performance; this is affected by both the use of thermal storage and by changes in the heat delivery profile. This is relevant when analysing DSM interventions but is not modelled elsewhere.
- The adverse effect that cold weather has on the performance of heat pumps; this is significant as it is possible that high electrical demands and low outside air temperatures will coincide.
- The effect of changes in the level of diversity that may occur after DSM interventions discourage the operation of heat pumps.

Several previous studies have taken a bottom-up approach and are able to take account of some of these factors (depending upon the detail used) but have not been used to assess the peak net-demand which might occur in the UK with diversity across the whole nation. Similarly, several studies have taken a top-down approach in assessing the peak demand which might occur. These provide good first estimations but the bottom-up approach used here provides additional insights.

It is shown that the electrification of domestic heating will result in significant increases in the peak net-demand. This can be reduced but not entirely mitigated by thermal storage and DSM. Ensuring appropriate installation of high-performance heat pumps in dwellings with improved levels of insulation has the potential to significantly reduce the net-peak.

2. Methodology

2.1 Sets of scenarios

Four sets of scenarios (25 in total) were simulated:

- The first seven scenarios relate to 40%, 60% or 80% of dwellings using ASHPs, with or without DSM (plus a seventh scenario in which ASHPs are not used). Climate and grid parameters relating to the 2030s were used. Improvements to the building stock and advanced ASHPs (performance equivalent to the current state-of-the-art) were assumed.
- Next, four scenarios illustrate the effect of the assumed improvements in the building stock and of using ASHPs with performance equivalent to the current mid-range. Climate and grid parameters relating to the 2020s were used.
- A set of six scenarios explore the sensitivity to different DSM parameters. Climate and grid parameters relating to the 2050s were used.
- A final set of eight scenarios explore the potential use of thermal storage. 60% of dwellings were taken to use ASHPs with climate and grid conditions relating to the 2030s.

2.2 Overview of models

A time-step modelling approach was applied with intervals of one minute. Several systems were modelled individually, as illustrated in Figure 1 and described in sections 2.3 through to 2.8. Additional details describing the thermal models and some aspects of the grid model are supplied in [28].

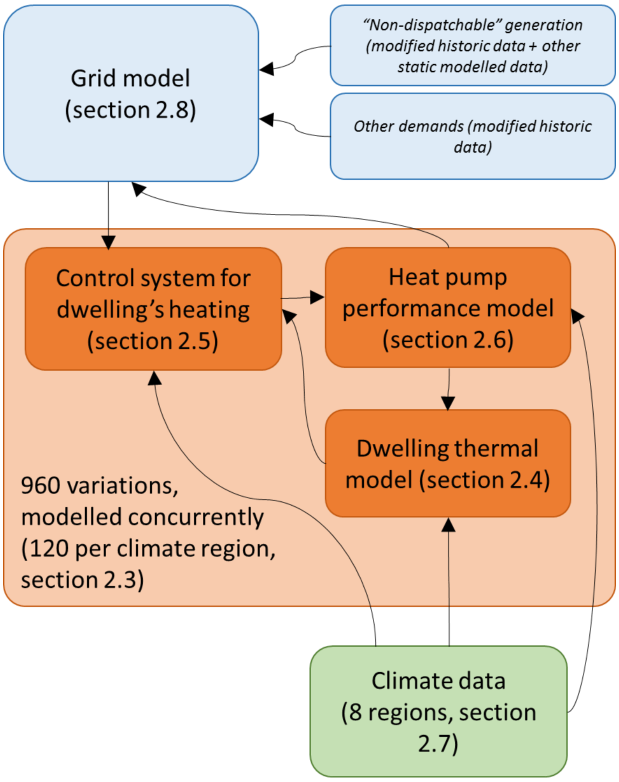

Figure 1: Interaction between elements of model

2.3 Diversity of demands across country

In order to adequately model the diversity exhibited by the demands, the heating demands of 960 dwellings were simulated concurrently. Preliminary results in Figure 2 demonstrate that diversity is not fully captured if less than 400 individual dwellings are simulated but that 960 is adequate. The power demands from each of the 960 dwellings were increased by a factor according to the proportion of dwellings using ASHPs in each scenario and their regional distribution, see Table 1 [29].

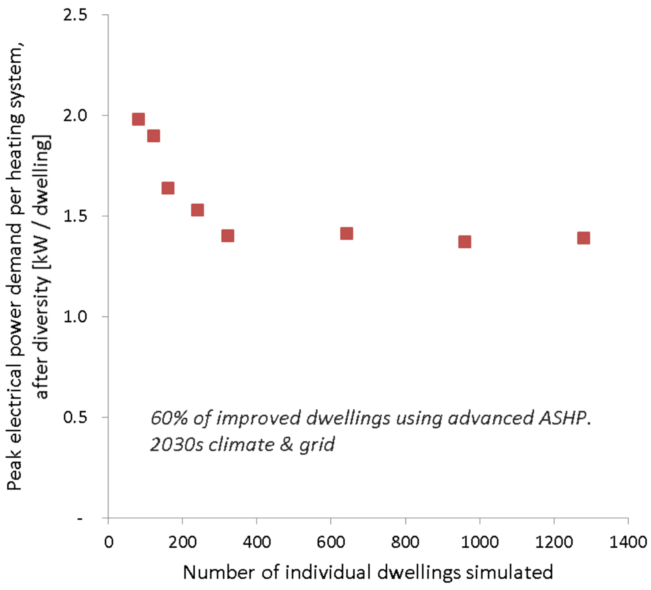

Figure 2: Effect of number of individual dwelling simulations on modelling results

Climate data for eight regions across Great Britain were used, with 120 different dwellings modelled within each region. The 120 dwelling permutations were formed from five building archetypes, eight internal temperature control profiles and three occupancy levels.

Table 1: Distribution of UK dwellings by region and type for 2011. Data from [28]

Region		Dwelling type	
Midlands	4.22 million	Semi-detached	7.13 million
SE England	3.59 million	Flat	7.74 million
Wales and SW England	3.65 million	Terraced	5.58 million
Greater London	3.34 million	Detached	4.56 million
NE England and Yorkshire	3.42 million	Bungalow	2.40 million
NW England	3.00 million		
East Anglia	2.50 million		
Scotland	2.37 million		

2.4 Building thermal model

A discrete lumped-capacitance thermal simulation was performed for each of the 960 dwelling permutations, see Figure 3.

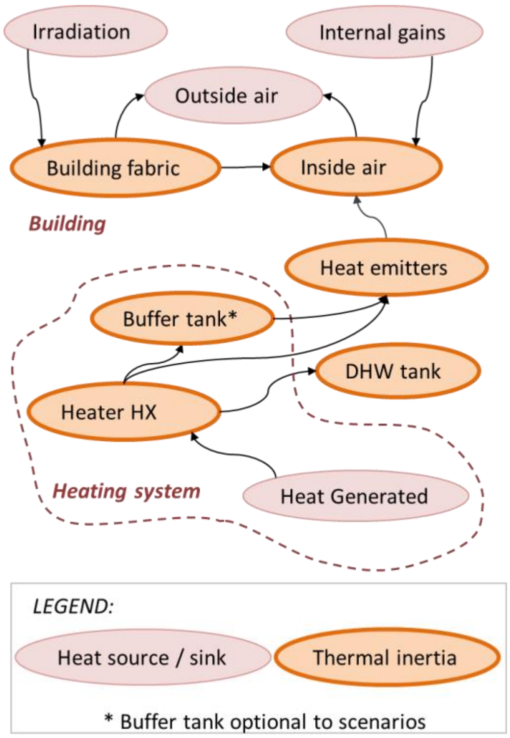

Figure 3: Elements of each dwelling thermal model

Five building archetypes were constructed: a semi-detached house, a detached house, a flat, a terraced house and a bungalow. Parameters for the thermal models were initially determined by calibration against data from detailed simulations [30] of dwellings selected as typical for the UK [31]. This provided realistic characteristics relating to thermal inertia. The inner and outer heat transfer coefficients were then adjusted to match the average heat loss coefficients for each building type [32]. The model was then run with climate data for 2011 and these characteristics were further adjusted to match the total annual heat demand for the entire population of buildings [29]. Radiator systems were scaled such that the design heat loss (inside air temperature 21°C, outside air temperature -1°C) was balanced with a flow temperature of 55°C.

A set of improvements across the building stock were assumed for scenarios apart from the second set in which the effect of these improvements was explored. The average air infiltration rate was halved, the outer skin heat transfer coefficient was reduced by 20% and the radiator systems were upgraded such that the design heat loss would be met with a flow temperature of 45°C. These improvement levels are ambitious but less than those suggested as possible elsewhere [33].

Internal gains and the active occupancy of occupants were modelled using a derivation of Richardson et al.'s [34] active occupancy model. Hot water demands from an empirical study [35] were assumed to be drawn from a 70-litre tank supplied by the ASHP.

In the scenarios involving DSM, some heat storage took place. In the scenarios in which thermal storage tanks were not used, this was achieved by raising the temperature of the fabric of the buildings by 2°C. In the final set of scenarios in which the effectiveness of using thermal storage tanks was analysed, two configurations were considered:

- Series. Water storage tanks were arranged in series between the ASHPs and the heat emitters; typical of current installation practice.
- Parallel. Water storage tanks were arranged in parallel with the ASHPs so that at any given time only one of them would be supplying the heat emitters. When not constrained by DSM, the ASHPs would switch to supplying the tanks as required in order to maintain their temperature at 50°C.

Different sizes of thermal storage tanks were considered (320kg, 640kg, 1280kg, 2560kg water) and a final scenario combined the use of the 1280kg storage tank with the 2°C increase in the temperature of the fabric of the buildings.

2.5 Control of ASHPs

Eight internal temperature control profiles were selected such that the average, standard deviation and range for different time periods of the day matched those noted in [36]. Random time delays of up to one hour and temperature variations of up to ±1°C were applied to each of the 960 dwellings.

Proportional controllers were used with each ASHP. That is, their target heat generation was proportional to the difference in temperature between the control target temperature at that time and the actual air temperature inside the dwelling. The control gain was selected for each dwelling such that at an outside air temperature of -1°C, a steady-state internal temperature of 21°C would be maintained. The offset for the proportional control was fixed at 1°C. The lack of a varying offset (i.e. an integrative element) to this control algorithm meant that the steady-state temperature achieved by the system varied by approximately 0.05°C for each 1°C change in the difference between the inside and outside air temperatures. This was considered acceptable for the current study though it is noted that actual control systems are likely to adopt a range of additional control elements. This control approach is only made possible by the use of the more recent ASHP models that are capable of modulating their output. In scenarios in which thermal storage was considered, on-off thermostatic control was used for heat delivery from the thermal storage tank to the dwellings, whilst the buffer tanks were maintained at 50°C.

In the scenarios in which DSM was considered, the effect of the DSM signal was to (a) Determine preference for using heat from the storage tank or the ASHP and (b) Adjust the target control temperature for the dwelling. In these scenarios, it was assumed that temperature reductions down to 2°C below the control temperature profile were acceptable. Although severe, these deviations occurred for a very small proportion of the time; the sum of the durations of all reductions in the target temperature, including those that were less severe than the full range, was set at 1% of the duration of the simulation by the way in which the DSM was applied. The maximum duration of individual DSM events and the minimum interval between them was not controlled. Although ISO7730 [37] suggests that long-term evaluation of thermal comfort can be achieved without reference to the duration of individual events (the total duration is used), it is clear that the conditions relating to the acceptability of DSM warrant research beyond the scope of the present study. It may be that further restrictions are appropriate and that these may further limit the effect that DSM could have on peak net-demand.

2.6 ASHP model

Standardised test data were obtained for two ASHP units [38], [39]. The test data provided the coefficient of performance (COP) of the ASHPs at different ambient air and flow temperatures, with other conditions standardised. The advanced (current state-of-the-art) unit was used in all simulations apart from those in the second set that explored the effect of using a mid-range ASHP.

The exergy efficiency of each unit was calculated at each condition for which test data were available. The exergy efficiencies at the four nearest test conditions (i.e. ambient air and flow temperatures) were then interpolated, geometrically weighted towards the nearest conditions. This was used to calculate the instantaneous COP and electrical power demands of each ASHP. This approach improves accuracy when simulated conditions tend towards the more extreme test conditions.

Thermal inertia was included in the ASHP model, in order to capture some of the dynamics of the operation of the units. The relevant coefficients were based upon the physical characteristics of the first unit [40].

2.7 Climate data

Test Reference Year (TRY) climate data do not typically capture the correlation between the weather at different locations at the same time so a modified approach was taken in this study. Historic climate data covering twelve winters at hourly resolution were obtained for eight locations across the UK [41]. The air temperature data for each of these locations were then transformed such that the mean and standard deviation of each entire series matched those from TRY data for that location.

In order to account for climate change, the relevant TRY data were obtained from the Prometheus project [42] which has projected data for the 2030s and 2050s. Median estimates based upon the “a1b” emissions scenario were used.

2.8 Grid model

In order to determine electrical demands net of non-dispatchable generation, it was necessary to employ models of total demand and of non-dispatchable supply. Historic grid generation data with a

5-minute timestep for the winters of 2009 to 2011 [43] was adapted in a way consistent with the "Market Rules" (MR) pathway assumptions generated by the Transition Pathways project [1] for the future scenarios. The method used to model the temporal characteristics of the electrical grid was similar to that described in [44] but with differences reflecting underlying data and the significance of ASHP heating and dispatchable generation to the present study. The grid model was single-node and did not model power flows through the transmission and distribution networks. Transmission and distribution constraints are a significant consideration and may be a major driver for the use of DSM in other contexts (e.g. [7], [8], [12]–[17]) but the present study focusses on peak power demands.

The MR pathway specifies a component of total demand relating to Electric Vehicle (EV) charging. This is unlikely to have the same profile as total demand and may be subject to DSM. However, to avoid ambiguity regarding the relative contribution of DSM used with EV charging, charging was assumed to follow a simple fixed profile with 25% occurring at a constant rate between 09:00 and 22:00 and the remainder at night-time. The simplification was justified by the relatively low contribution that EV charging makes to overall demand in this pathway. Similarly, the potential effect of DSM on household appliance demands was not modelled.

Table 2: Future annual generation assumed. Adapted from [42], [44].

	Historic [TWh]	2020 [TWh]	2035 [TWh]	2050 [TWh]
Total Demand	320	370	450	512
Wind	6	50	112	171
Nuclear	63	49	89	125
Other non-dispatchable	3	37	64	64
Electric vehicle demand	N/A	2	23	38

Note that these totals are for comparison; they do not include the effect of the heating considered in the present study.

Wind generation was assumed to follow a profile generated using algorithms developed by Sturt and Strbac [46]. Separate profiles with 30-minute timesteps were generated for twelve winter seasons and scaled to match the total wind generation corresponding to the MR pathway assumptions for each scenario. Nuclear generation was considered to be non-dispatchable and followed the historically observed profile, scaled to match the appropriate total. Tidal, non-pumped hydro and CHP generation were also assumed to be non-dispatchable.

In the cases in which DSM was simulated, the objective of the DSM interventions was to reduce the peak net-demand (net of non-dispatchable generation). A threshold was set at the demand that was not exceeded for 99% of the duration of the equivalent simulation without DSM. When net-demand was above this threshold, the signal was progressively increased in order to discourage consumption (by decreasing the temperature control set-points in the dwellings and encouraging use of heat from thermal storage tanks). Section 3.4 explores the sensitivity of the results to this.

When net-demand was below the threshold, the DSM signal was set to encourage storage of thermal energy (in either the fabric of buildings or storage tanks). By storing thermal energy *whenever* net-demand was below the threshold, this approach produced optimistic results in terms of the potential of DSM to reduce peak net-demand but pessimistic results in terms of the impact on total consumption.

3. Results and Discussion

3.1 Overview

Net-demand duration curves for each of the twelve winter periods in one scenario are illustrated in Figure 4 along with a darker curve derived from all twelve. The year-on-year results exhibit some variation; the extremes observed across the twelve winter periods are captured by the “all results” curve but it seems unlikely that the extremes that would occur over a longer period are reflected. The plots in Figures 5 to 8 correspond to all twelve of the 90-day winter seasons.

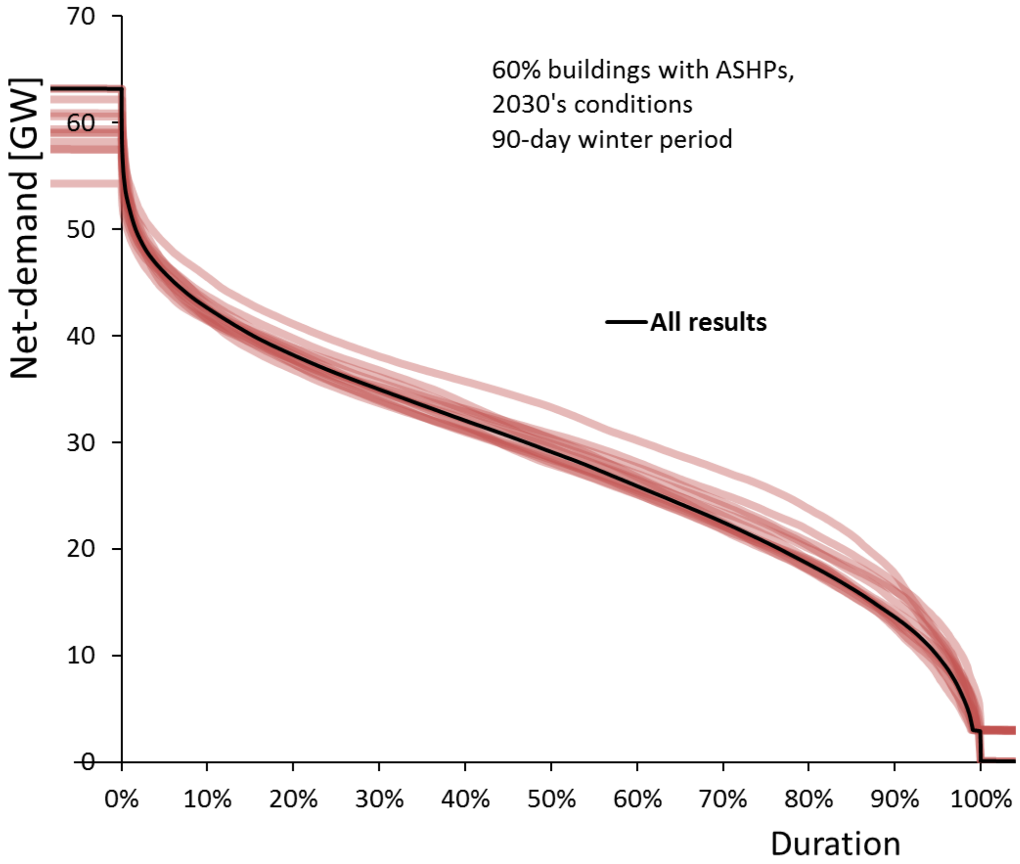

Figure 4: Year-to-year variation in net-demand duration curves

The peak net-demands for each scenario are given in Table 3. There is a small duration (around 30 minutes, 0.002% of the duration of the twelve winter periods simulated) for which an extremely large net-demand occurs. Because of the possibility that some unmodelled mechanism would mitigate these peaks, the peak increase that occurs for 0.05% of the duration of the simulation is also given.

Table 3: Peak net-demand occurring in each scenario

Scenario Set	Notes	Peak for <0.002% duration [MW]	Increase [MW]	Peak for <0.05% of duration [MW]	Increase [MW]
	(historic)	*49300*	-	*48700*	-
Central scenarios 2030s climate & grid (thermal storage in fabric of buildings when DSM used)	No ASHP	51600	-	49500	-
	40% ASHP, no DSM	57600	6000	54600	5100
	40% ASHP, DSM	55400	3800	53400	3900
	60% ASHP, no DSM	62500	10900	58100	8600
	60% ASHP, DSM	59300	7700	56300	6800
	80% ASHP, no DSM	67600	16000	62300	12800
	80% ASHP, DSM	62900	11300	59700	10200
Effect of conditions 80% with ASHPs, 2020s climate & grid	No ASHP	52300	-	51300	-
	Mid-range ASHP, Current building standards	106700	54400	100300	49000
	Advanced ASHP, Current building standards	88500	36200	82500	31200
	Advanced ASHP, Improved building standards	73300	21000	68300	17000
DSM thresholds 80% with ASHPs, 2050s climate & grid	No ASHP	54300	-	50800	-
	80% ASHP , no DSM	69100	14800	63500	12700
	DSM threshold 53.5GW	64900	10600	61000	10200
	DSM threshold 50.7GW	65100	10800	60800	10000
	DSM threshold 56.1GW	65000	10700	61300	10500
	DSM threshold 58.5GW	65100	10800	61700	10900
Thermal storage 60% with ASHPs 2030s climate & grid	1280kg thermal storage in series, No DSM	87100	35500	80200	30700
	1280kg thermal storage in series, DSM temperature range +0/-2°C	71300	19700	69800	20300
	No thermal storage tank, DSM temperature range +0/-2°C	59800	8200	56700	7200
	320kg thermal storage in parallel, DSM temperature range +0/-2°C	58200	6600	55500	6000
	640kg thermal storage in parallel, DSM temperature range +0/-2°C	57400	5800	54800	5300
	1280kg thermal storage in parallel, DSM temperature range +0/-2°C	57200	5600	54700	5200
	2560kg thermal storage in parallel, DSM temperature range +0/-2°C	57100	5500	54600	5100
	1280kg thermal storage in parallel, DSM temperature range +2/-2°C	57300	5700	54600	5100

The peak net-demands associated with the three scenarios without ASHPs are similar (51.6GW to 54.3GW). This result is specific to the parameters associated with the MR pathway. The increased contribution from wind generation reduces the increase in peak net-demand that would result from the overall increase in demand but reduces the total electrical energy supplied by dispatchable generating plant (and therefore their capacity factors) by far more.

The wide range of peak demands illustrates the sensitivity of these results to the assumptions and conditions of each scenario. Studies that suggest potential pathways to a low carbon energy system should apply caution in assuming a particular value for future generation capacity requirements.

3.2 Results relating to central scenarios

Figure 5 illustrates the net-demand duration curves for the first set of scenarios.

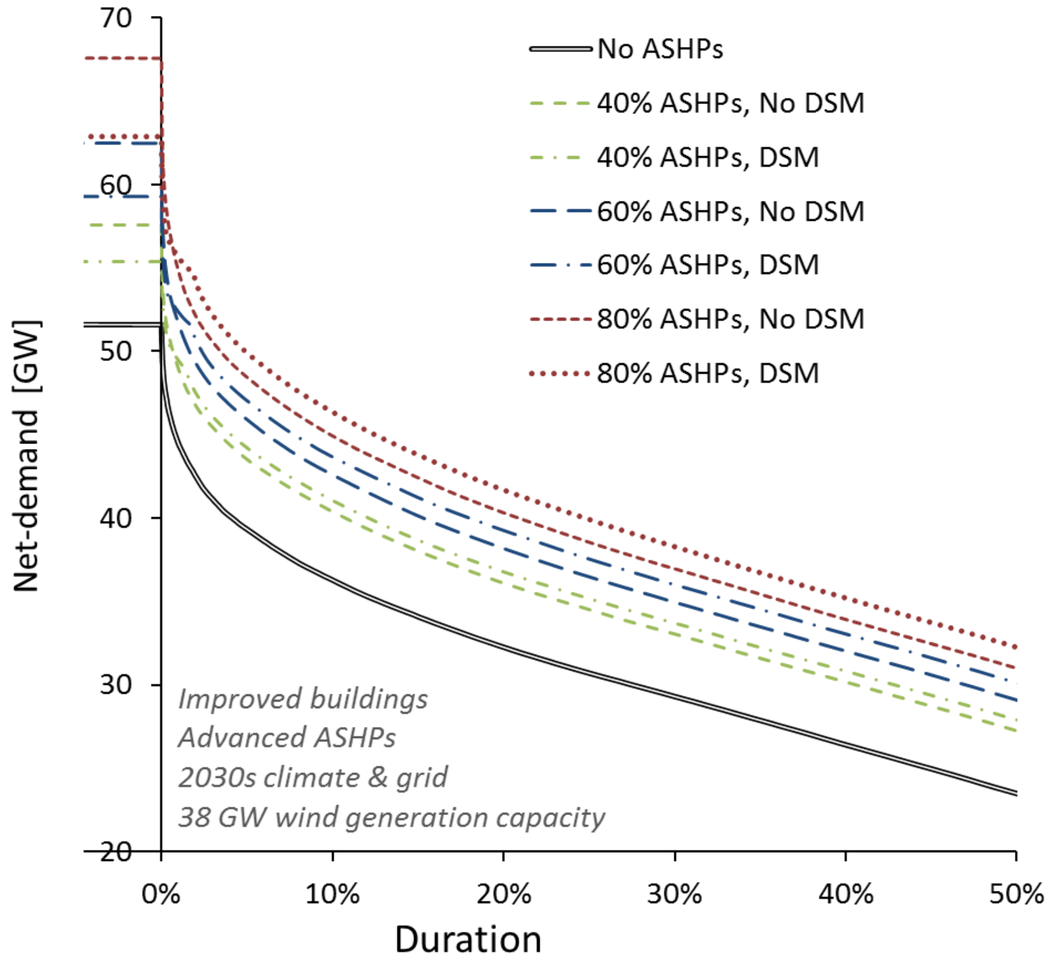

Figure 5: Net-demand duration curves for central scenarios

With 60% of dwellings using ASHPs, the increase in the peak net-demand is 11GW, changing to 16GW or 6GW if 80% or 40% of dwellings use ASHPs, respectively. There is an approximately proportional relationship between the number of ASHPs and the increase in demand. DSM achieves reductions in the increase in peak net-demand of 37%, 29% and 29% for the scenarios involving 40%, 60% and 80% of dwellings employing ASHPs, respectively.

Of particular interest are the steep increases in the maximum net-demand that occur during the small proportion of time during which high heating demands and extended low wind generation coincide. In many cases, it is possible to use DSM to limit the increase in the net-demand to 20% of the increase which would otherwise occur for 99.9% of the duration of the simulations. However, if the remaining 0.1% of the duration is considered then the increase can only be limited to 50%. Not accounting for these infrequent events will lead to an underestimation of the dispatchable generation capacity required.

3.3 Effect of operating conditions

Figure 6 illustrates results for the second set of scenarios, in which the effect of not improving building standards or the performance of the ASHPs which are widely used is explored.

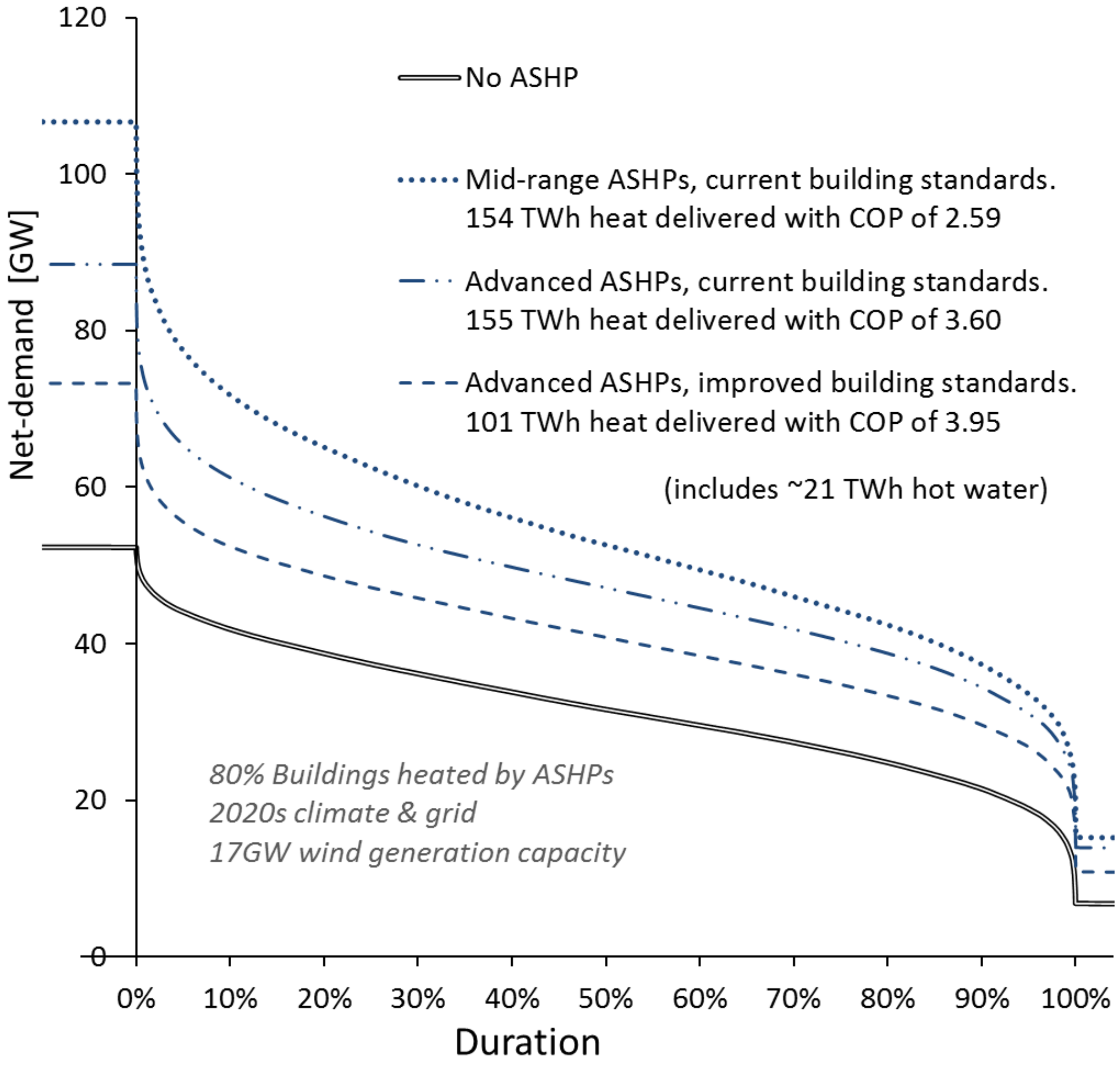

Figure 6: Net-demand duration curves for different operating conditions

Using the mid-range ASHPs with present day building standards leads to an increase in peak net-demand requirement associated with the heat pumps of 54GW (2.6kW per dwelling). This result is consistent with that suggested in [10]. Using advanced ASHPs reduces the increase to just over 36GW; consistent with the "non-DSM" case in [7]. The advanced ASHP units achieve an average (heat demand weighted) COP of 3.60, compared to 2.59 for the mid-range units under the same conditions.

By improving the insulation level of the building stock, electrical demand can be further reduced to an increase in peak net-demand of 21GW. Improved insulation levels reduce the absolute heat demand (from 155TWh to 101TWh, average for the 90 day period), but also reduce the rate at which heat must be delivered, enabling the use of lower flow temperatures. Along with the more effective heat emitter systems, the average COP achieved by the ASHPs is increased from 3.60 to 3.94. These modelled improvements across the building stock are not considered realistic for 2020 and are included for comparison purposes only.

3.4 Effect of Demand Side Management

Figure 7 shows the demand characteristics for the third set of scenarios, relating to conditions for the 2050s. This includes four scenarios in which DSM is applied with different criteria.

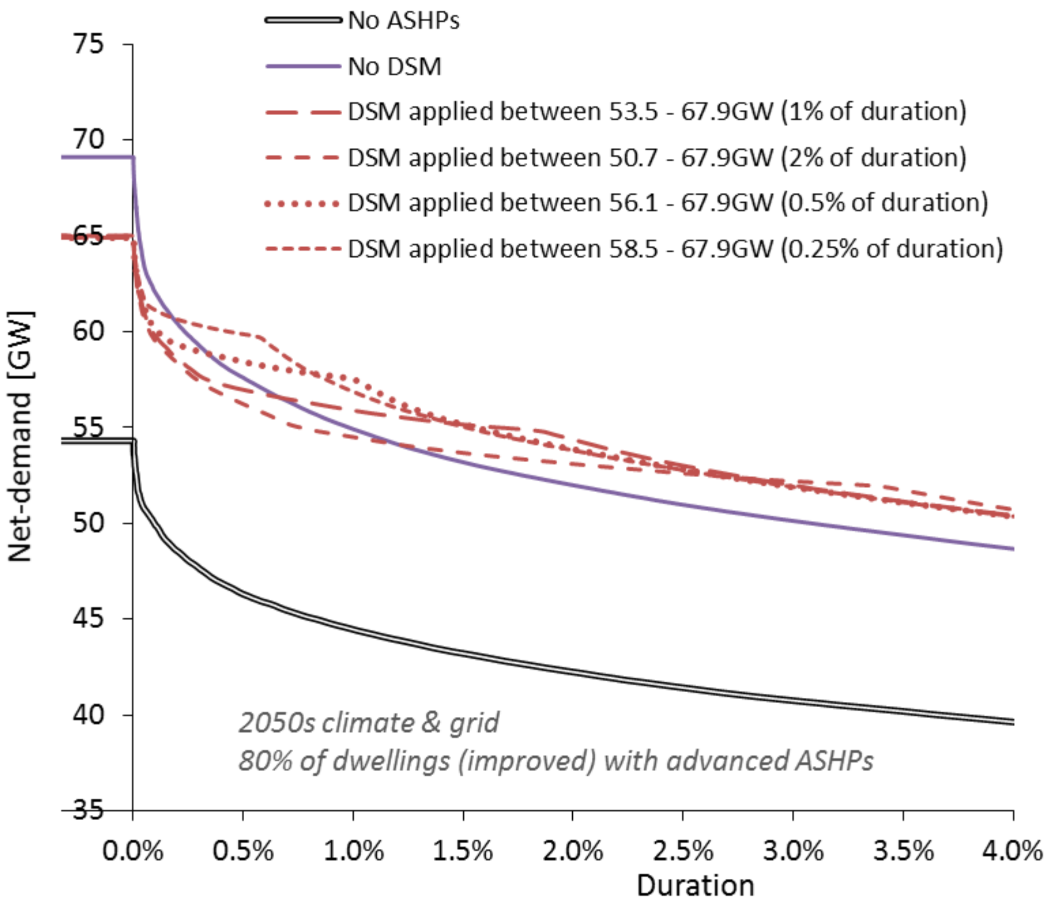

Figure 7: Net-demand duration curves for 2050 scenarios

A reduction in the peak net-demand of over 4GW is achieved through the use of DSM. This is a significant proportion (28%) of the increase that would otherwise occur as a result of the use of ASHPs (15GW) but is less than earlier studies have suggested. These plots demonstrate a slight increase before a decrease in gradient below their peak net-demands, corresponding to demand being shifted to times when net-demand is lower.

The effect of using different thresholds at which the DSM starts to discourage the operation of ASHPs is relatively small for the alternatives considered in this study. This implies that there are periods during which net-demand is high (e.g. low wind generation, high demands) that exceed the duration that dwellings can remain above the minimum acceptable temperature without heating. The reduced peak net-demand observed when the DSM system is used is due to the lower steady-state heat demands when the internal air temperature in almost all of the dwellings is lower, not due to the condition in which the temperatures of some dwellings are still cooling and there is still scope for flexibility. The DSM system's main scope of influence is exhausted before net-demand drops back below the threshold value. A DSM system that reduces the demand from ASHPs irrespective of dwelling temperatures would almost certainly be counter-productive as occupants would inevitably turn to other sources of heating. In an all-electric system, these sources of heating would include electrical resistive heating that would increase demand more than if the ASHP had not been constrained, exacerbating the problem.

3.5 Effect of thermal storage

Figure 8 compares the net-demand duration curves with thermal storage options.

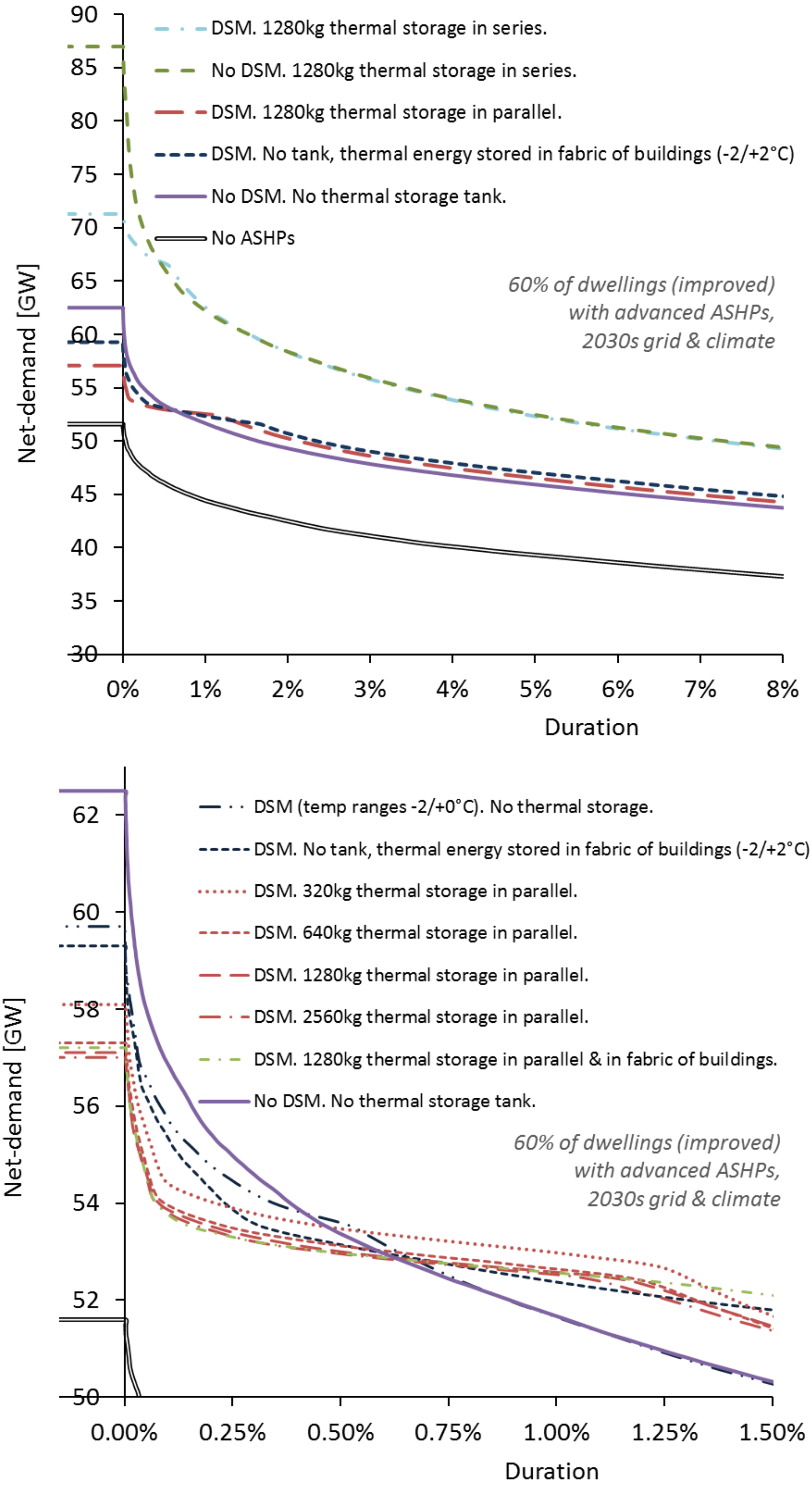

Figure 8: Net-demand duration curves with different thermal storage options

Arranging thermal storage in series with ASHPs carries a performance penalty. This more than offsets the increased flexibility, resulting in an increase in peak net-demand of 20GW, (1.2kW per dwelling). This is 11GW more than the equivalent scenario without thermal storage. Modulating an entire population of ASHPs to run continuously at half power is generally more effective than cycling though the same population of ASHPs, continuously operating half of them at full power.

Arranging the thermal storage tanks in parallel with the ASHPs is more promising. Using 640kg tanks enables the increase in peak net-demand to be reduced by over 2GW (i.e. a reduction of 5GW relative to the scenario in which DSM is not used). A performance penalty, averaging around 400MW results from the need to supply heat to the storage tanks at a higher temperature than to the dwellings. It is possible that this could be reduced by optimised scheduling but cannot be eliminated. Reducing the tank size below 640kg reduces the extent to which the peak net-demand can be mitigated but it is not clear that tank sizes above 640kg are beneficial.

The additional thermal energy stored in the fabric of the buildings by raising their temperature by 2°C is insufficient to make a significant difference to the peak net-demand which occurs, given the potential duration of low wind, high demand events. Options to increase the thermal inertia in the fabric of buildings through heavier construction or more novel methods such as phase change materials are not explored here.

Given the large potential for an initial response to DSM signals applied to ASHPs but the challenges involved in using it to alleviate longer term increases in net-power demand, it seems likely that DSM of ASHPs is more suited to objectives with a shorter time frame such as reducing the rate at which dispatchable generating plant is required to vary its output.

4. Concluding Remarks

The increase in the peak demand, net of non-dispatchable generation, that may arise due to the operation of heat pumps has been investigated for the UK. In order to investigate this issue, an integrated modelling approach was developed in which dynamic thermal models of archetype dwellings and heat pumps were combined with a model of the electrical grid supply mix. The increase in the peak net-demand caused by 60% of dwellings using ASHPs could be as low as 11GW, or 5.5GW if thermal storage is used with DSM designed to reduce it. However, without improvements to the building stock, the increase (due to 80% of dwellings using current mid-range ASHPs) could exceed 54GW. The peak net-demand only occurs for a small fraction of the time; ignoring these outlying results (e.g. by selecting a shorter or less severe simulation period) would cause an underestimation of generation capacity requirements.

In conjunction with appropriate thermal storage, DSM has the potential to halve the increase in the peak net-demand that would occur (for the range of ASHP adoption rates considered). This is a significant reduction but not as great as might otherwise be assumed; the effect of occasional extended cold low wind events is hard to mitigate. It is possible that the DSM of ASHPs is better suited to achieving other objectives such as reducing the rate at which the output from dispatchable plant needs to be ramped. Although an increase in thermal storage could achieve better flexibility, suitable configuration is necessary in order to ensure that the performance penalty of such an approach does not outweigh its benefits.

The electrification of domestic heating is likely to increase peak net-demand. However, the actual extent of this increase is sensitive to the conditions in which the heating takes place. There are various options for decreasing the electrical power demands of ASHPs. These include improved insulation in buildings, more effective heat emitter systems, control systems that are optimised to the operating characteristics of ASHPs along with appropriate advice to users and the increased use of higher performing ASHPs. With these measures, the actual increase in the peak net-demand due to the use of ASHPs will be far more manageable.

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